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2012

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Recommended Citation

Michalas, L; Garg, A; Venkattraman, A; Koutsourelis, M; Alexeenko, Alina A.; Peroulis, Dimitrios; and Papaioannou, G, "A study of field emission process in electrostatically actuated MEMS switches" (2012). *School of Aeronautics and Astronautics Faculty Publications*. Paper 6.

<http://dx.doi.org/http://dx.doi.org/10.1016/j.microrel.2012.06.019>

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A study of field emission process in electrostatically actuated MEMS switches

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Abstract

A study of field emission process in MEMS-based capacitor/switch-like geometries is presented. High resolution current-voltage characteristics up to breakdown have been obtained across micro-gaps in fixed-fixed Metal-Air-Metal and Metal-Air-Insulator-Metal structures. In metallic devices the I-V dependence reveals Fowler–Nordheim theory effects. In the presence of insulator the process is found to be limited by the film conductivity following Poole–Frenkel dependence. The data analysis reveals the major importance of surface asperities on the onset of the field emission process while it is also presented that charge transfer may occur between metal and insulator surfaces even in the presence of micrometer scale gaps.

1. Introduction

Due to their potentially low cost, low power consumption and high linearity microelectromechanical devices are quite promising devices for several sensors and actuation applications including RF components [1,2]. Although several switches devices have been under research and development for nearly two decades, their commercialization is still hindered by reliability issues. Since understanding of the device failure mechanism is of vital importance for the microelectronics industry, MEMS reliability is a topic that still attracts a great academic and industrial research interest.

Charging of solid dielectric layers, mainly arising during device actuation is a critical reliability issue in RF MEMS capacitive switches. Under the presence of very high electric field charges are injected from electrodes and stored in the dielectric. The build up of parasitic charge is responsible for undesirable switch behaviour and limits its lifetime [3-5]. Therefore this phenomenon has been studied intensively by several authors employing a variety

of techniques [6-14].

Another very important reliability issue for electrostatically actuated MEMS switches, which has not yet received appropriate attention [15], is the understanding of the field emission that occurs across micro gaps formed between metallic and other surfaces. In such micro gaps ranging from nanometer scale up to a few micrometers the electric field increases locally reaching potentially very high values capable to onset field emission process. This process involves the transfer of charges between the two surfaces due to the high electric field and can lead from device performance degradation and/or failure.

Presently it is well accepted that the electrical breakdown in such small gaps does not follow the conventional Pachen's law [16]. Recent experimental results of currents generated across micro gaps in MEMS like structures before breakdown revealed the Fowler–Nordheim field emission as the main responsible mechanism [17]. Moreover, the strong non uniform charging, mapped with Kelvin Probe Force Microscopy

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and reported by R. Herfst et al. [18] indicates charge injection through a field emission mechanism.

The present paper presents high-resolution current-voltage characteristics measured across micro gaps in fixed-fixed Metal-Air-Metal (MAM) and Metal-Air-Insulator-Metal (MAIM) structures. The aim of the study is to investigate the field emission process in electrostatically actuated MEMS structures and reveal that due to field emission currents, charge transfer occurs between metallic and insulating surfaces. This process constitutes an additional mechanism that contributes to dielectric charging in MEMS switches even in the absence of contact between the insulator layer and the moving armature and even before actuation, when the pull-in voltage is sufficiently large.

2. Theoretical background

Fowler – Nordheim (FN) theory describes the emission of electrons from a metal due to very high electric field. This emission process takes place through sharp asperity paths, where the electric field is locally enhanced by several orders of magnitude. Therefore such field emissions in relatively low applied voltages should not be considered as an unexpected phenomenon. The typical signature of this conduction mechanism is the exponential dependence of current on bias above some threshold voltage. In terms of measured current (I) versus applied bias (V) the Fowler – Nordheim equation is expressed as [19, 20]

$$I_{FN} = aV^2 \exp\left(-\frac{b}{V}\right) \quad (1)$$

where

$$a = \frac{1.54 \times 10^{-6} \alpha \beta^2}{1.1 \Phi} \exp\left(\frac{9.87}{\Phi^{1/2}}\right) \quad (2)$$

and

$$b = \frac{6.5 \times 10^9 \Phi^{1/2}}{\beta} \quad (3)$$

where α is the effective emitting area and β the field enhancement factor. Equation (1) is obtained from the Fowler – Nordheim effect taking into account that the current density (J) and the electric field strength (E) are $J = I/\alpha$, $E = \beta V$ and that $u(y) = 0.95 - y^2$, $t^2(y) = 1.1$ and

$$y = 3.79 \times 10^{-5} \frac{E^{1/2}}{\Phi} \quad (4)$$

By plotting the $\ln(I/V^2)$ against $1/V$ (the so called Fowler-Nordheim plot) a straight line is obtained which is the signature of the mechanism. Given the work function of the metal (Φ), it is possible to estimate from the intercept the emitting area and from the slope the field

enhancement factor. The field enhancement factor and the emitting area are determined by the geometry of the emitting asperity.

Inside an insulating film the most common conduction mechanism is Poole-Frenkel (PF) conductivity. The current in terms of applied bias in this case is expressed as

$$I_{PF} = C \left(\frac{V}{d}\right) \exp\left(-\frac{q - \sqrt{\frac{q}{\pi \epsilon}} \cdot \frac{V}{d}}{kT}\right) \quad (5)$$

where d is the dielectric film thickness and C is a constant proportional to Poole – Frenkel conductivity. By plotting the $\ln(I/V)$ against \sqrt{V} a straight line is obtained which is the signature of the mechanism.

3. Device fabrication and experiment

Fig. 1 shows an SEM image of a typical MEMS device that was fabricated at Purdue University, USA and measured at the University of Athens, Greece. The fabrication details are outlined in [8] and are not repeated here. The fixed-fixed beam is a thick ($>6 \mu\text{m}$) electroplated Ni beam. The beam is made so thick in order to suffer a negligible deflection when biased against its Au actuation pad underneath it. Two different fabrication processes were completed in order to result in two nominal distances between the Au pad and the Ni beam: $1.5 \mu\text{m}$ and $3.5 \mu\text{m}$. Some devices were fabricated without any dielectric covering the Au pad, while others included a PECVD 50-nm Silicon Nitride layer over the Au pad (Fig. 1 shows a device without a dielectric layer).

The field emission current through the MEMS device was measured with a Keithley 6487 picoampere meter, which provided the required bias in the range of 0-550V that was applied to the bottom electrode. The measurements were performed in a Biorad cryostat in vacuum (10^{-3} Bar) at room temperature.

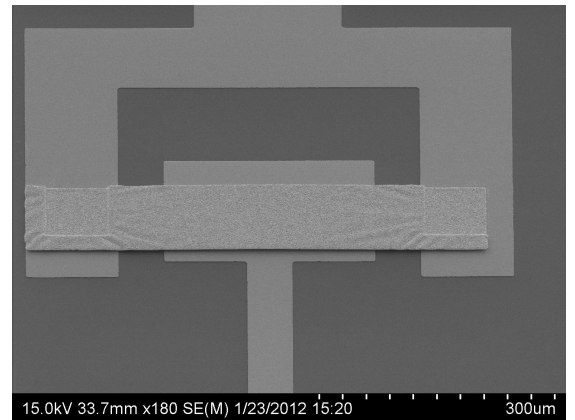


Figure 1: SEM of a typical measured MEMS device.

4. Results and discussion

The Fowler Nordheim plots of Metal-Air-Metal (MAM) devices with gap spacing of 3.5 μm and 1.5 μm are presented in Figs. 2 and 3. The straight lines obtained in both cases are clear evidence that the field emission process before breakdown obeys the Fowler-Nordheim mechanism. Moreover, the areas labeled [A] and [B] show the occurrence of a first field emission followed by breakdown and a second field emission followed by breakdown respectively. Table 1 summarises the values of field enhancement factor (β) and emitting areas (α), calculated by the slope and the intercept of the linear regions in each case (2),(3).

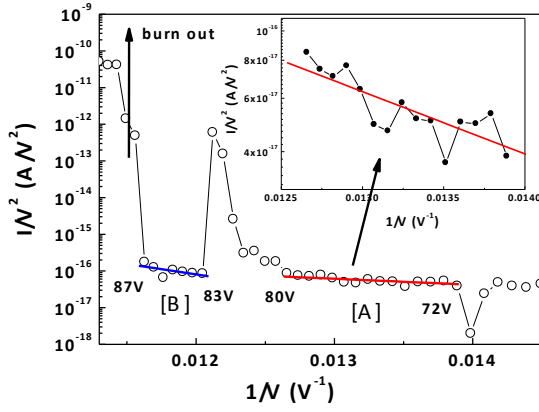


Figure 2: FN plot for 3.5 μm gap. The inset graph presents in detail the region [A]

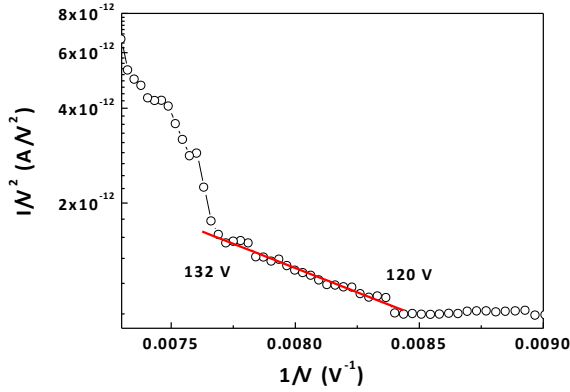


Figure 3: FN plot for 1.5 μm gap.

In order to understand the device behavior it is essential to take into account that a field emission process generally takes place through sharp asperity paths. In the vicinity of such an asperity the electrostatic field is locally enhanced by a parameter β , reaching the intensity $E = \beta V$. Therefore in a metal surface the onset of the field emission is expected to take place through the sharpest asperity when the local electric field reaches threshold intensity. Considering that during the breakdown an asperity smoothing occurs [17], the process is expected to restore in higher voltages by a different slope corresponding to a

less sharp asperity, thus lower β and/or higher α values.

Table 1: Experimentally obtained field enhancement factors (β) and emitting areas (α)

	β (10^7m^{-1})	α (m^2)
3.5 μm [A]	3.9	2.86×10^{-25}
3.5 μm [B]	3.1	1.97×10^{-24}
1.5 μm	2.1	8.9×10^{-20}

The threshold field intensity for the onset of such a process has been calculated in the order of 2-3 V/nm [21], a result which is in good agreement with the threshold voltages and corresponding asperity parameters obtained in our case (Figs. 2-3 and Table 1). More precisely in case of 3.5 μm gap the onset of the first field emission process occurs around 72 V leading to a local field intensity of 2.8 V/nm, while the second onset occurs around 83 V, that correspond to field intensity of 2.6 V/nm. This also explains the reason that higher voltage is required for a field emission in the device with the smaller gap. In this case the threshold voltage for the field emission is obtained around 122 V, a value that corresponds again to an electric field of 2.6 V/nm. Thus we can conclude that the most important parameter that determines the onset and the current-voltage dependence of the field emission process is the geometry of the surface asperities and not the gap spacing between two surfaces. Indeed the electric field is enhanced by decreasing the distance, d , between the two electrodes as $E = V/d$, however this increase is low comparable with the increase that occurs in the vicinity of a sharp asperity ($E = \beta V$). In this case the electric field may increase locally by several orders of magnitude leading to field emission process even at very low voltages [18,22]. Moreover it must be also taken into account that the presence of an asperity is a completely random effect since neither spatial periodicity has been obtained nor dependence on wafer location, switch design or place of the sample [23]. Therefore different results may observed even on identical devices [18,22]

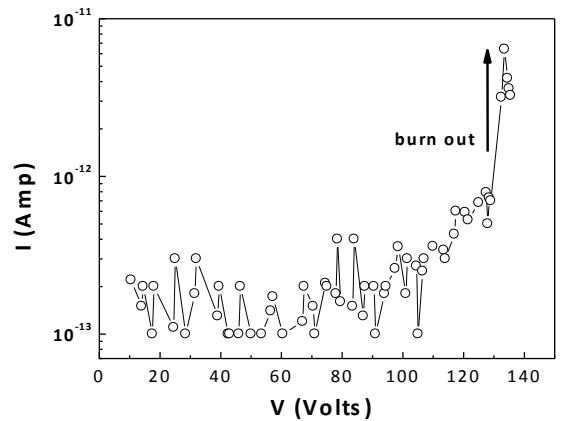


Figure 4: Current-Voltage characteristics of MAIM structure

Regarding the Metal-Air-Insulator-Metal (MAIM)

structures, the current voltage characteristics are presented in Fig. 4.

A clear evidence of current flow through the device above 90 V is presented, indicating the transfer of charges across the air gap, 1.5 μm for the present sample.

The current flow follows the Fowler-Nordheim mechanism across the gap (I_{FN}) and Poole-Frenkel mechanism through the dielectric film (I_{PF}). Since the same current flows across the sample $I_{FN}=I_{PF}$ and the applied bias is divided so that $V=V_{FN}+V_{PF}$, the magnitude of the current will be limited by the mechanism that exhibits the smaller variation with the corresponding bias (V_{FN} or V_{PF}). Thus for lower bias levels where the voltage drop across the dielectric film is low, the FN mechanism, (1), will dominate. As the applied bias increases, the field emission tends to increase and the PF mechanism, (5), will determine the current voltage behavior. The presence of the two mechanisms, FN at lower and PF at higher bias levels are clearly shown in Figs. 5, and 6.

The straight line obtained in Fig. 5 (FN plot) indicates that in the range of 90 V up to 105 V the field emission process is the dominant mechanism. Above 105 V the straight line is no longer consistent with the experimental results denoting the change in the device conduction mechanism. In this region the current voltage dependence is in good agreement with Eq. (5) that describes the PF conduction, Fig. 6 shows the fitted PF plot. For bias levels above 130 V the device is driven in burn out.

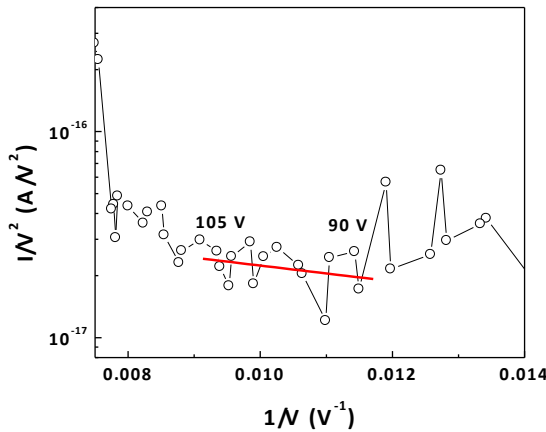


Figure 5: FN plot for the current through Metal –Air – Insulator-Metal structures

Furthermore, it is important to mention that since field emission process takes place even at large gaps between metal bridge and the insulating film and therefore contributes to charging. This process can take place in the down state condition when only part of the bridge is landed on the insulating film or even before actuation. Since the most important parameter that determines the onset of the process has been found to be the geometry of surface asperities, smooth metal surfaces are required in order to mitigate the field emission current.

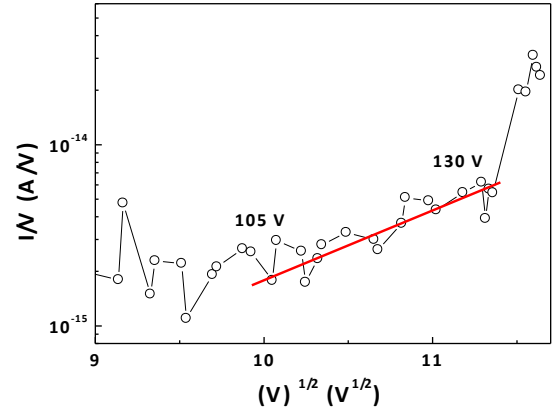


Figure 6: PF plot for the current through Metal –Air – Insulator-Metal structures

Conclusion

The field emission process in Metal-Air-Metal and Metal-Air-Insulator-Metal fixed-fixed structures has been investigated through high resolution current voltage characteristics. The results reveal that the most important parameter that determines the field emission process is not the gap spacing between the electrodes but the surface asperity geometry. Charge transfer takes place through the sharpest asperity when the locally enhanced electrostatic field intensity reaches the value 2-3 V/nm. The process occurs also between metal and insulator surfaces even at micrometer scale gaps. In this case the conduction is mainly determined by dielectric conductivity. The results suggest that dielectric charging may occur even without contact between the metal bridge and the insulating film in MEMS switches and that MEMS structures require as smooth as possible metal surfaces.

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